Long Term Cloud Property Datasets from MODIS and AVHRR Using the CERES Cloud Algorithm

Patrick Minnis, Kristopher M. Bedka, David R. Doelling
NASA Langley Res Center, USA

Sunny Sun-Mack, Christopher R. Yost, Qing Z. Trepte, Sarah T. Bedka, Rabindra Palikonda, Benjamin R. Scarino, Yan Chen, Gang Hong, Rajendra Bhatt
SSAI, USA

Research supported by NASA CERES Program & NOAA CDR Program

2015 EUMETSAT Meteorological Satellite Conference, Toulouse, France, 21 -25 September

Objectives & Motivation

• Create a long-term consistent cloud property data record from polar-orbiting satellites using the same algorithm, or at least one that is as close as possible

• CERES algorithm used to interpret longest record of radiation budget measurements
  - radiance conversion to flux based on CERES scene ID
  - CERES since 2000
  - ERBE record being revised using CERES-like AVHRR clouds

• Important for climate to have variety of interpretations to assess uncertainties

Imagers and Satellites

• MODerate-resolution Imaging Spectroradiometer (MODIS)
  - Terra (2000 – present), Aqua (2002 – present)

• Advanced Very High Resolution Radiometer (AVHRR)
  - TIROS-N, NOAA satellites, MetOp (1978-present)

• Visible Infrared Imaging Suite (VIIRS)
  - Suomi National Polar-orbiting Partnership (SNPP, 2012 - present)
  - Joint Polar Orbiting Satellite System (JPSS, 2017 - ?)

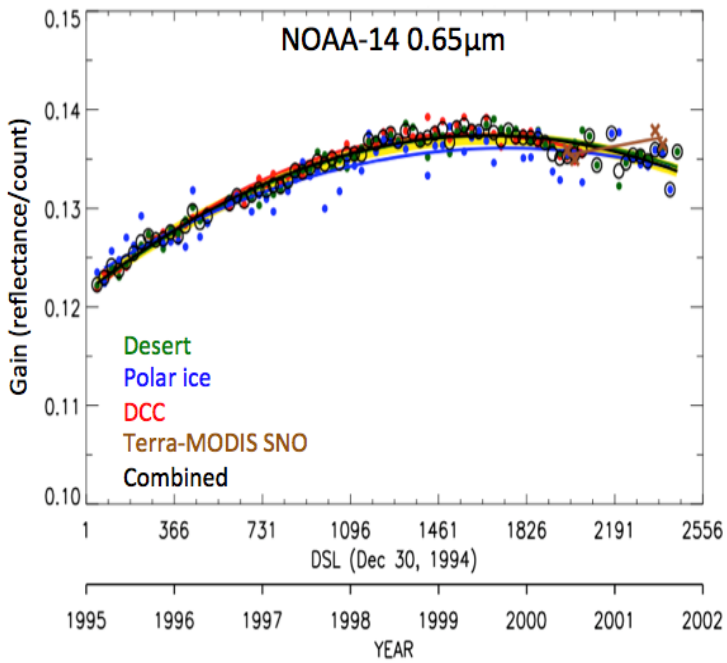
Challenges to Developing Long-term Cloud Climatologies

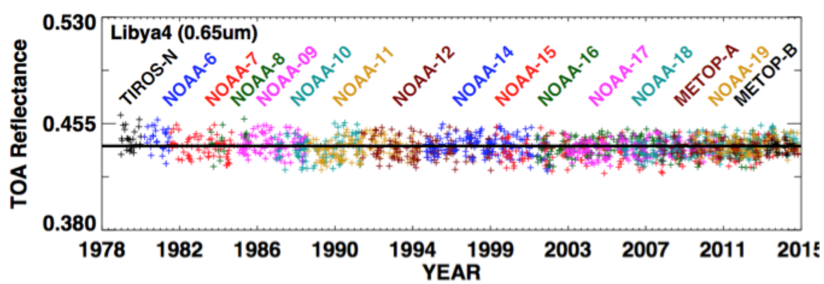
- Multi-channel calibration stability
  - AVHRR, no onboard solar channel calibration
  - AVHRR, dual and single gain instruments
  - noise
- Multi-instrument spectral response function (SRF) differences
  - even in same series, SRFs can differ
- Varying orbit configurations
  - NOAA drifting satellites (nominally 0730 and 1400 ECTs)
    - *some maintained, some not*
  - MetOps (0930 ECT) and NOAA-17 (nominally 1000 ECTs)
  - Terra (1030 ECT), Aqua/SNPP (1330 ECT)
- Auxiliary data variations
  - CERES uses fixed GEOS-5 product
- Sensor resolution differences
  - MODIS: 1 km, AVHRR GAC ~2 km, VIIRS: 375-750 m
- Imager channel complement differences

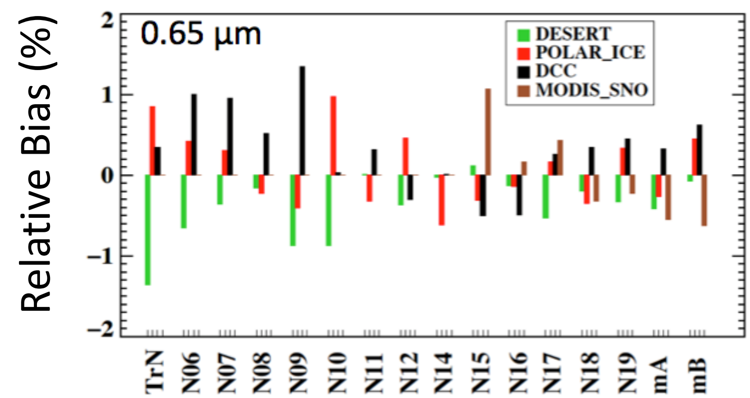
ISCCP was first face these challenges and paved the way

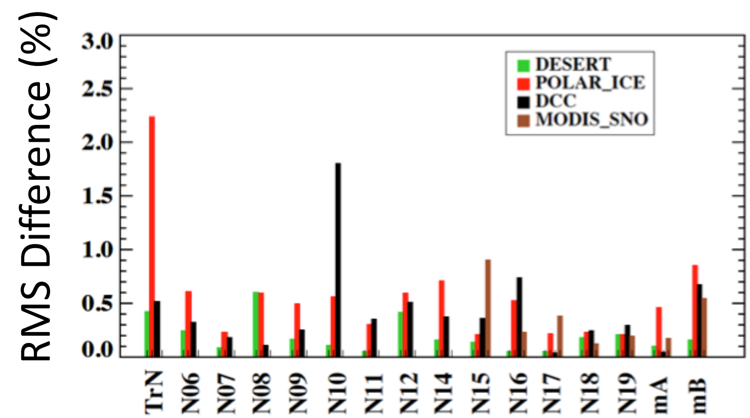
Calibrations

- Attempted to normalize all to Aqua MODIS C5, assumes lifetime stability
    - Terra MODIS and SNPP VIIRS visible channel (0.65 µm)
    - Terra 3.7-µm channel
    - AVHRR visible channels (0.65 µm) *[Doelling et al. 2015, Bhatt et al. 2015]*
        - *combines SNO, DCC, & Pseudo-invariant calibration sites (PICS)*
        - *no attempt to adjust thermal channels*









- RMS generally < 1% among the techniques

Methodologies: Satellite ClOud and Radiative Property retrieval System (SatCORPS)

- CERES Edition 4: same as Edition 2 *(Minnis et al. 2011)*, except
  - uses 0.65 (τ), 3.8 (*Re*, phase), 11 (*Tcld*), and 12 (detection, phase)
  - roughened hexagonal column ice crystal model *(Yang et al. 2008)*
  - 13.3 µm for high cloud *Tcld* supplement, polar night detection, multilayered
  - low cloud heights from regional lapse rates of *Sun-Mack et al. (2014)*
  - more sensitive cloud mask for cumulus + 1.38 µm for thin cirrus detection
  - 6.5 µm used for polar night cloud detection, 1.24 µm for τ over snow
  - new thickness parameterizations, OT adjustment of top heights
  - GEOS-5 NWA input throughout (Ed2 used GEOS-4 to 2008, then GEOS-5)
  - multilayer clouds and multispectral *Re* retrievals

- AVHRR Edition 1: SatCORPS-A1 (for 5-channel, 3.8-µm day only)
  - uses 0.65 (τ), 3.8 (*Re*, phase), 11 (*Tcld*), and 12 (detection, phase)
  - roughened hexagonal column ice crystal model *(Yang et al. 2008)*
  - low cloud heights from regional lapse rates of *Sun-Mack et al. (2014)*
  - visible or BTD(11-12) used over snow => low τ
  - new thickness parameterizations
  - MERRA NWA input throughout
  - SW and LW fluxes based on new radiance correlations with CERES

- VIIRS Edition 1, same as CERES Ed4, except
  - no 6.5 or 13.3 µm used
  - revised water droplet reflectance model

Properties Saved

Standard, Single-Layer VISST/SIST

	Cloudy Pixels Only
0.65, 0.86, 1.6 µm Reflectances	**Mask**, Phase
3.7, 6.7, 10.8 µm Temp	**Optical Depth τ**, IR emissivity
12 or 13.3 µm Temp	**Cloud effective particle size**
Broadband TOA Albedo*	Liquid/Ice Water Path
Broadband OLR*	**Effective Temp**, height, pressure
Clear-sky Skin Temp *(Scarino et al. 2013)*	Top/ Bottom Pressure
Pixel Lat, Lon	Top/ Bottom Height
Pixel SZA, VZA, RAZ	**Overshooting tops** ** *(Bedka et al. 2010)*

Multi-Layer, CERES Only

Upper & lower cloud

Multilayer ID (single or 2-layer)	
effective temperature	optical depth, thickness
effective particle size	ice or liquid water path
height, top/base height	pressure

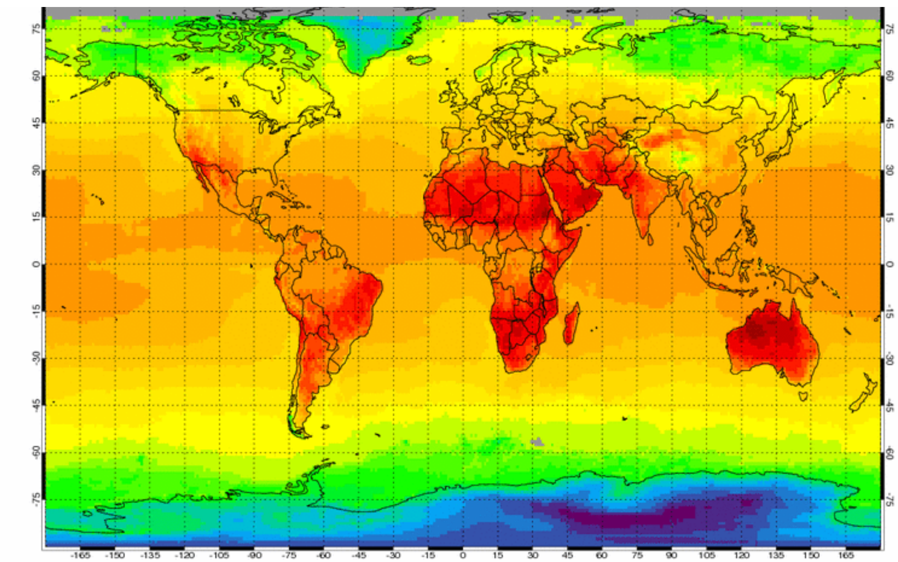
*CERES only has fluxes in SSF (cloud properties averaged to CERES scanner footprint)

**Only for AVHRR, used in CERES to alter height of OTs

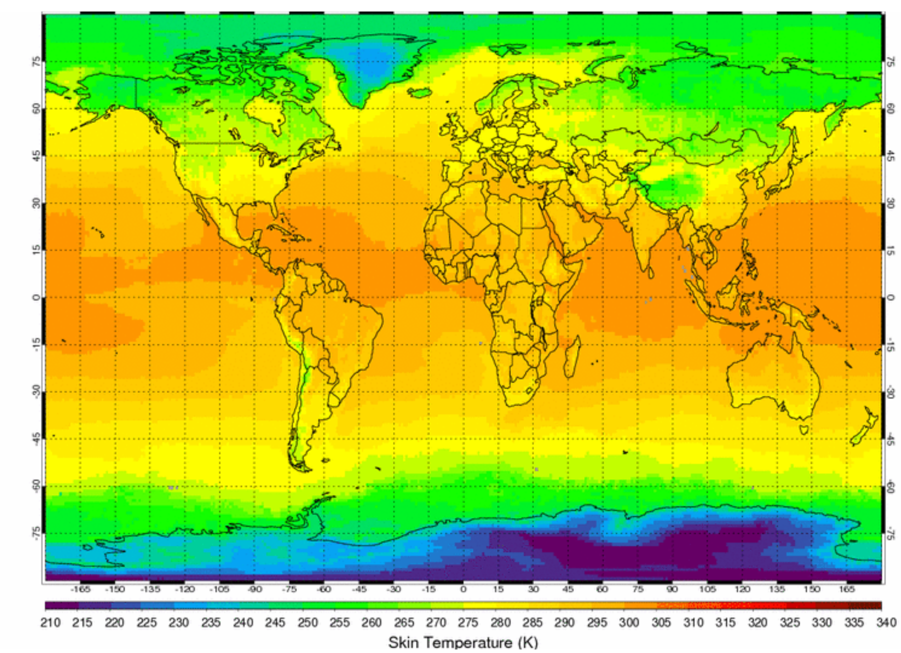
Mean Clear-sky Tskin, October 2008

Other parameters

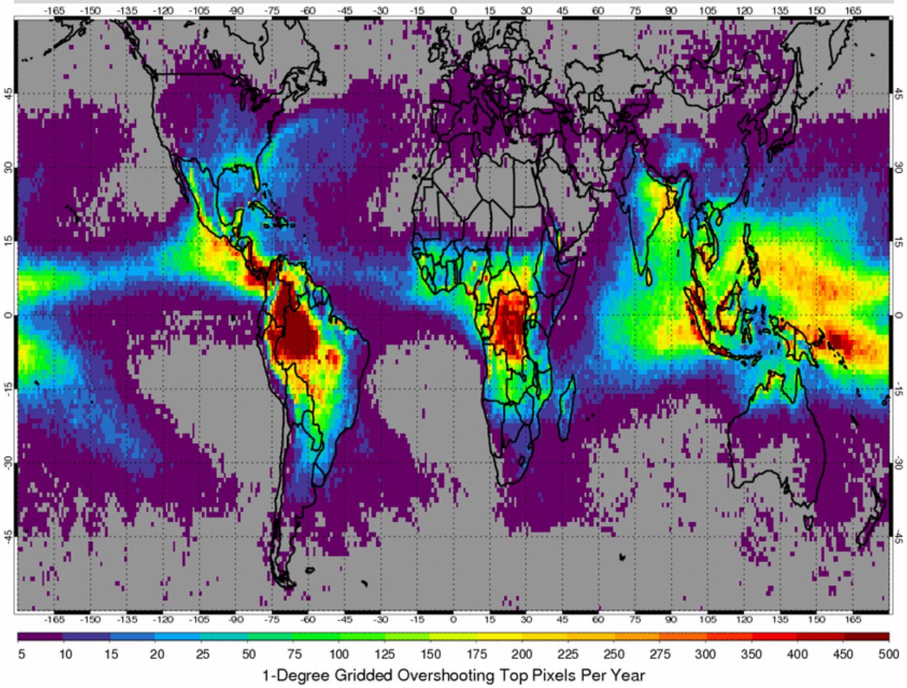
Day



Night



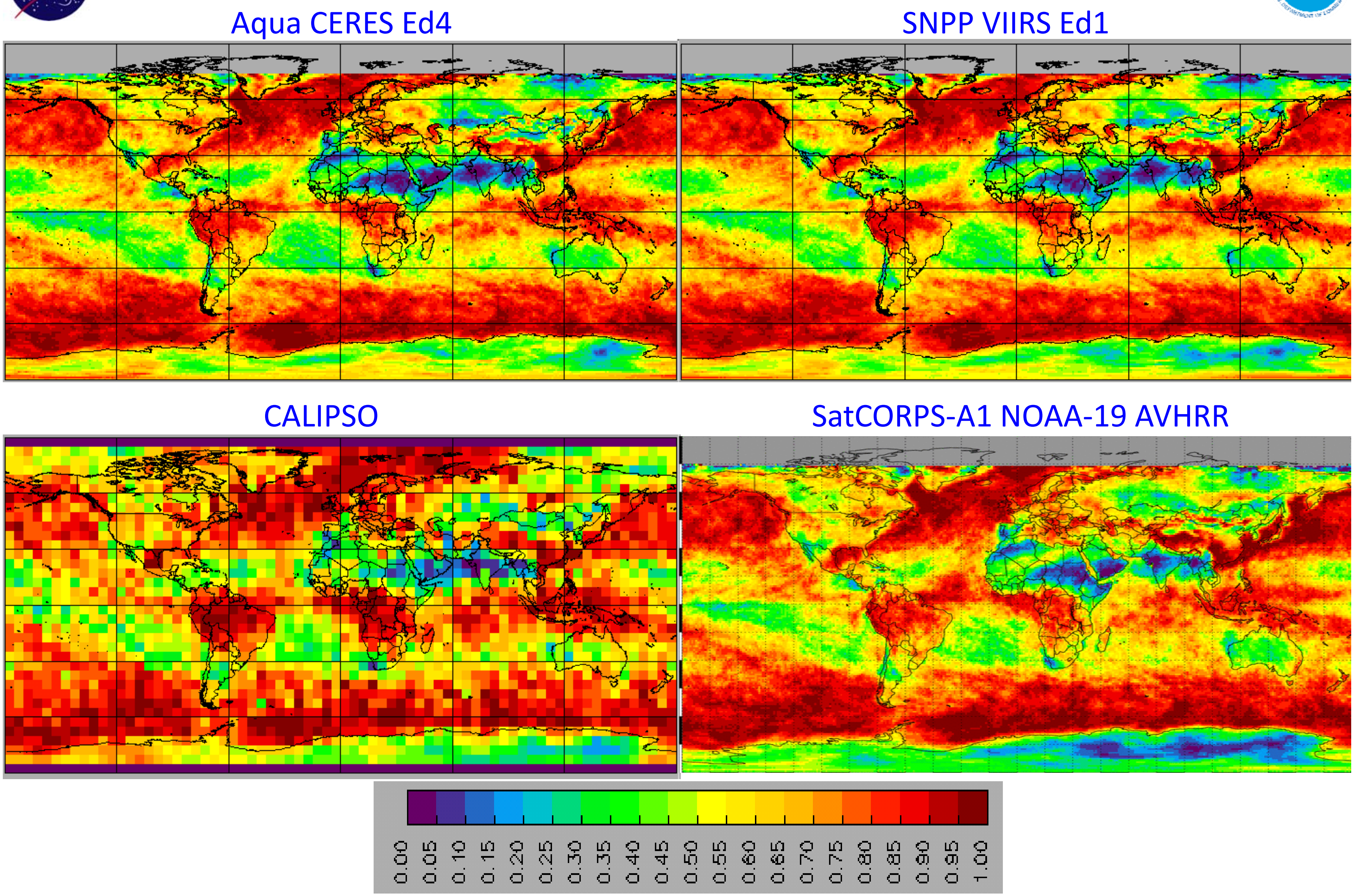
Overshooting Top Detections
17 years, 1-3 AM/PM LT



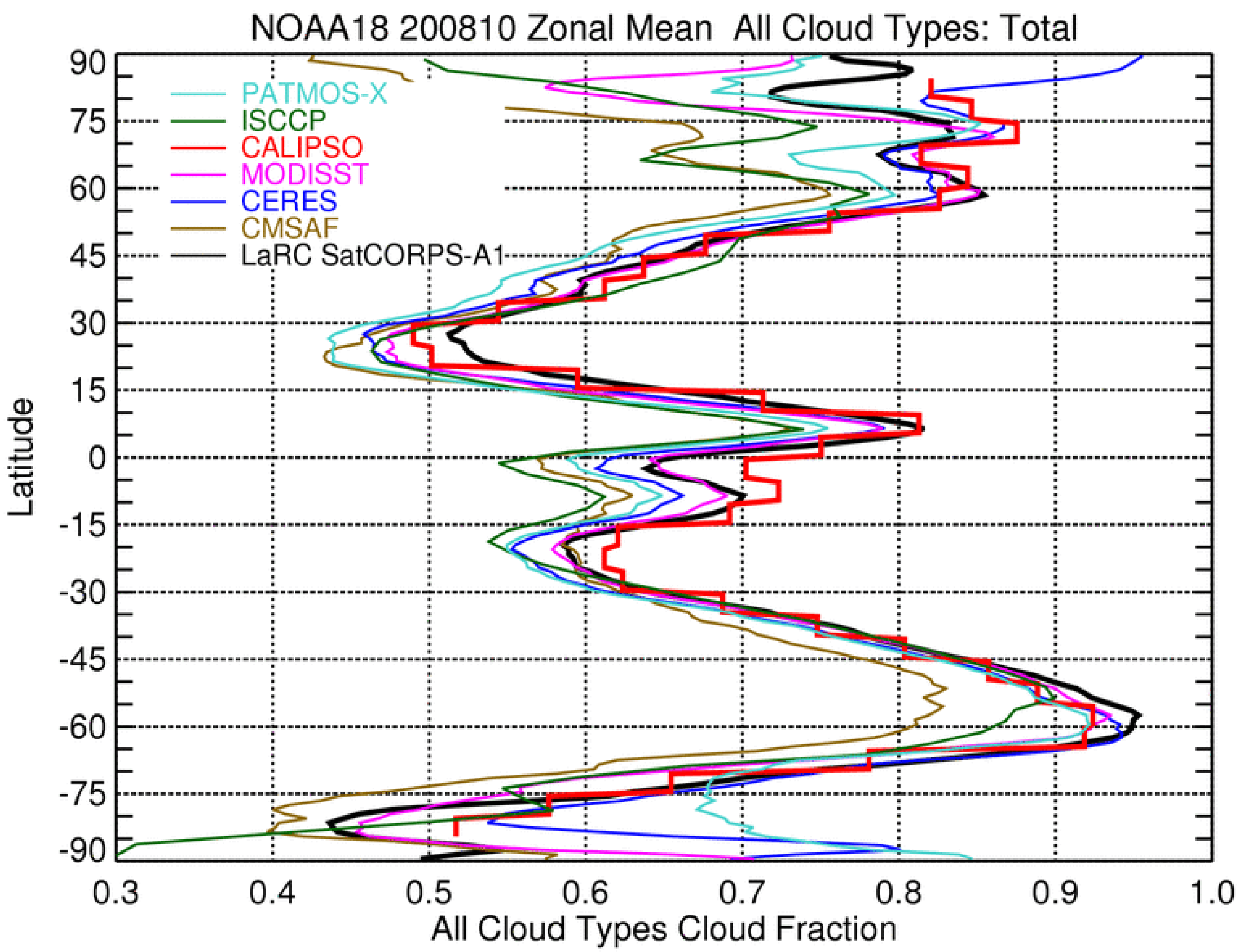
Validation & Comparisons

Land Surface Type, Geographic Region, and Time of Day of Comparison	Fraction of Correctly Identified AVHRR Clear and Cloudy Pixels	Number of Matches
DAYTIME (0° ≤ SZA < 82°)		
Land, 60 S – 60 N, No Snow/Ice Cover	0.848	285570
Land, Polar, No Snow/Ice Cover	0.878	30665
Ocean, 60 S – 60 N, No Snow/Ice Cover	0.875	844315
Ocean, Polar, No Snow/Ice Cover	0.943	70071
Land & Ocean, Global, Snow/Ice Covered	0.825	404235
NIGHT (SZA ≥ 82°)		
Land, 60 S – 60 N, No Snow/Ice Cover	0.870	288234
Land, Polar, No Snow/Ice Cover	0.875	23678
Ocean, 60 S – 60 N, No Snow/Ice Cover	0.888	879729
Ocean, Polar, No Snow/Ice Cover	0.951	100782
Land & Ocean, Global, Snow/Ice Covered	0.715	727283

Mean Cloud Fractions, Day, February 2012



Cloud Fraction Comparisons with Other Methods
Day + Night, October 2008



Means	
CALIPSO	0.703
CERES	0.671
SatCORPS	0.697
MODIS-ST	0.679
PATMOS-X	0.631*
CLARA	0.623
ISCCP	0.649

** cloudy + probably cloudy*

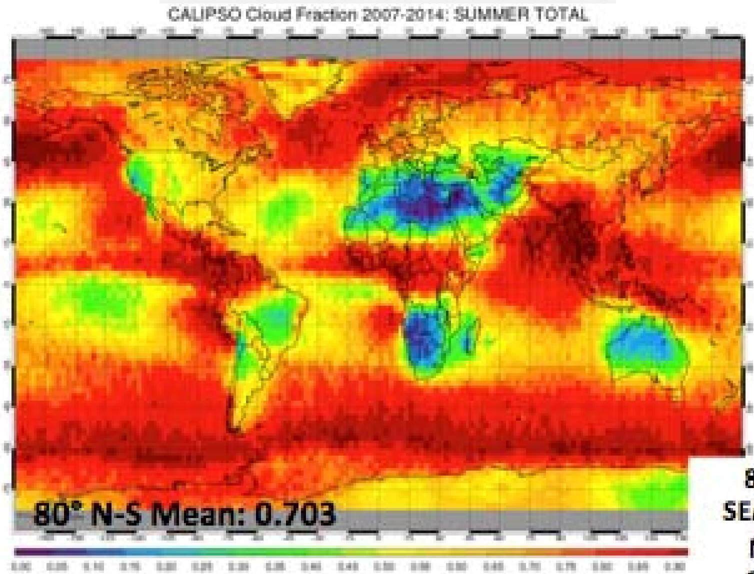
- Results typical for all months
- SatCORPS close to CALIPSO, but 0.026 < CERES Ed4

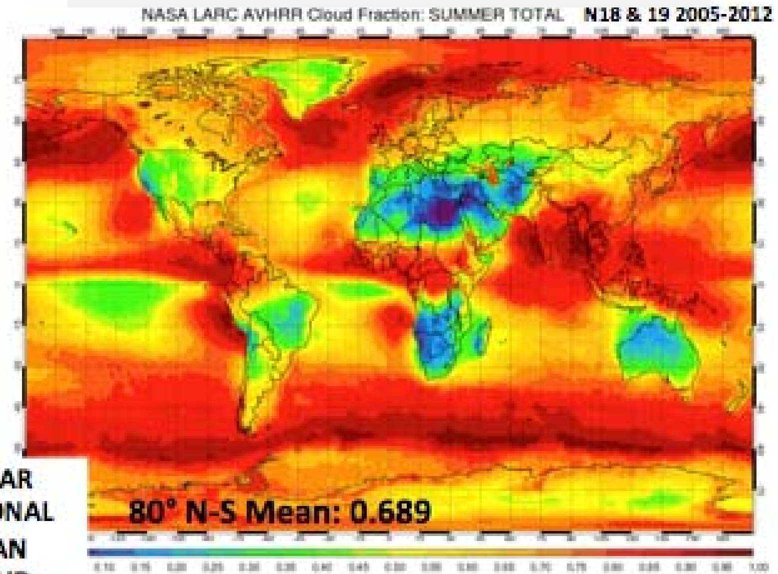
Multiyear Seasonal Mean Cloud Fractions: Day + Night

CALIPSO (2007-2014)

SatCORPS N18/19 (2005-2012)

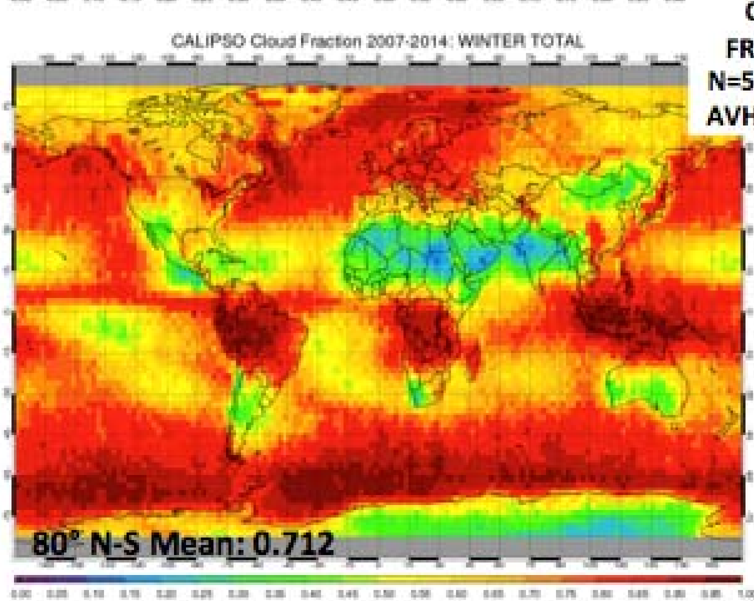
JJA

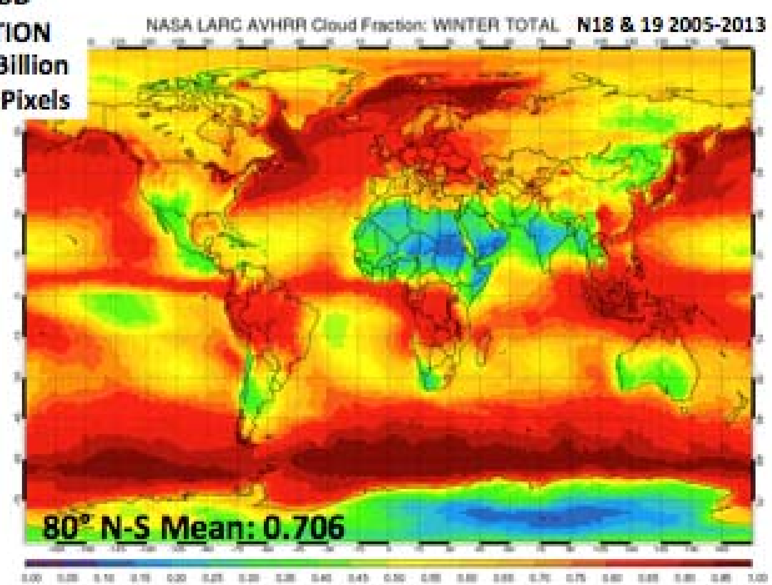




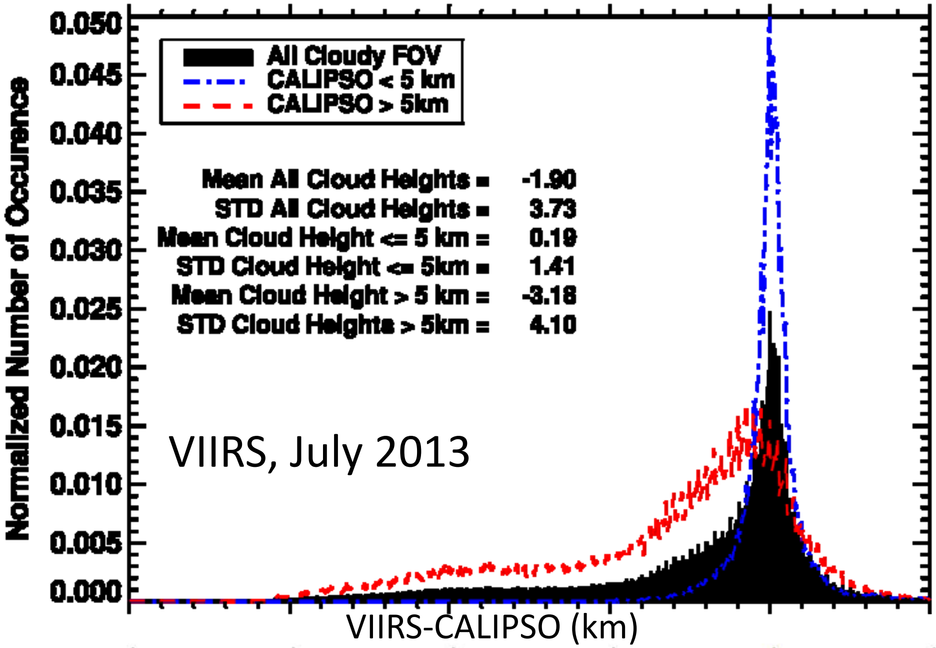
8-YEAR
SEASONAL
MEAN
CLOUD
FRACTION
N=50+ Billion
AVHRR Pixels

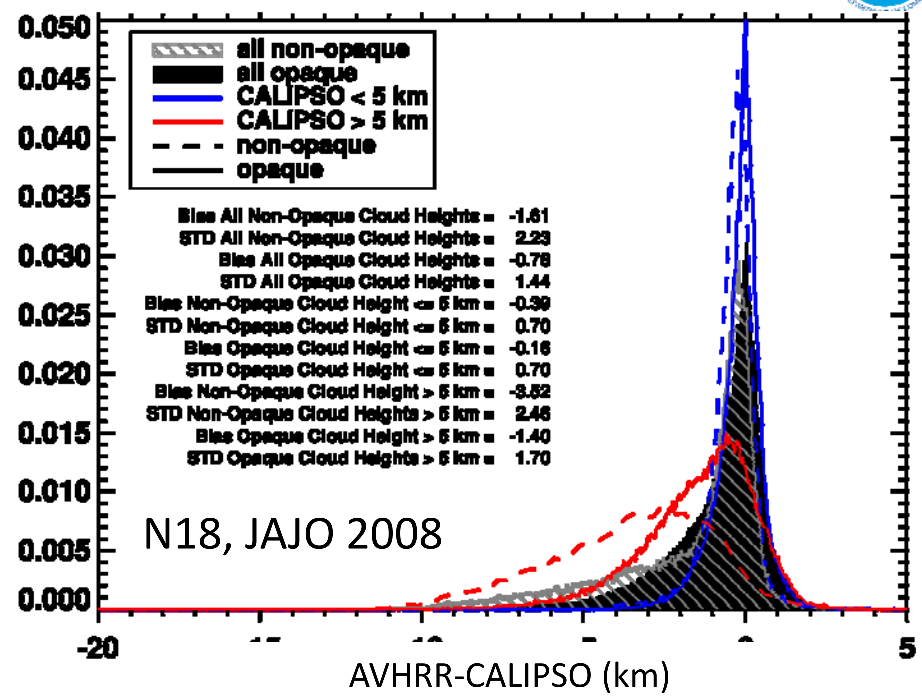
SON

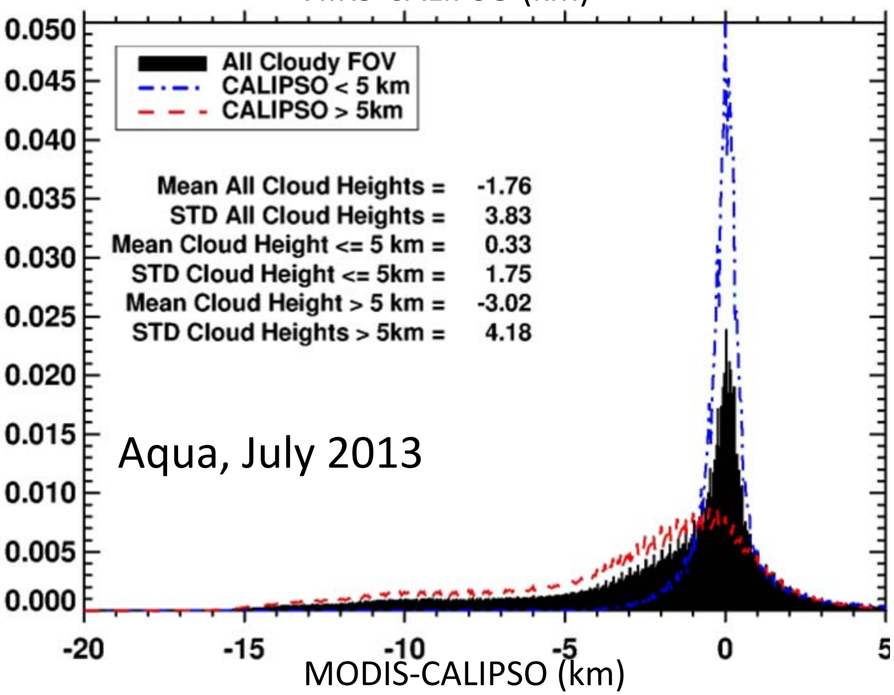




Cloud-Top Height Differences: Imager – CALIPSO, 60°N – 60°S







All = Single + Multilayer

- Low cloud tops: -0.24 to 0.33 km bias
  - SDD: 1.41 – 1.75 km
- High cloud tops: -3.52 to -3.02 bias
  - SDD: ~4.1 km

Single Only

- Low cloud tops: -0.24 to 0.33 km bias
  - SDD: 1.41 – 1.75m
- High cloud tops: -3.52 to -3.02 bias
  - SDD: ~4.1 km

Impact of Spatial Resolution on Cloud Property Retrievals

Mean cloud properties from 30 days of MODIS data over central USA, April 2008

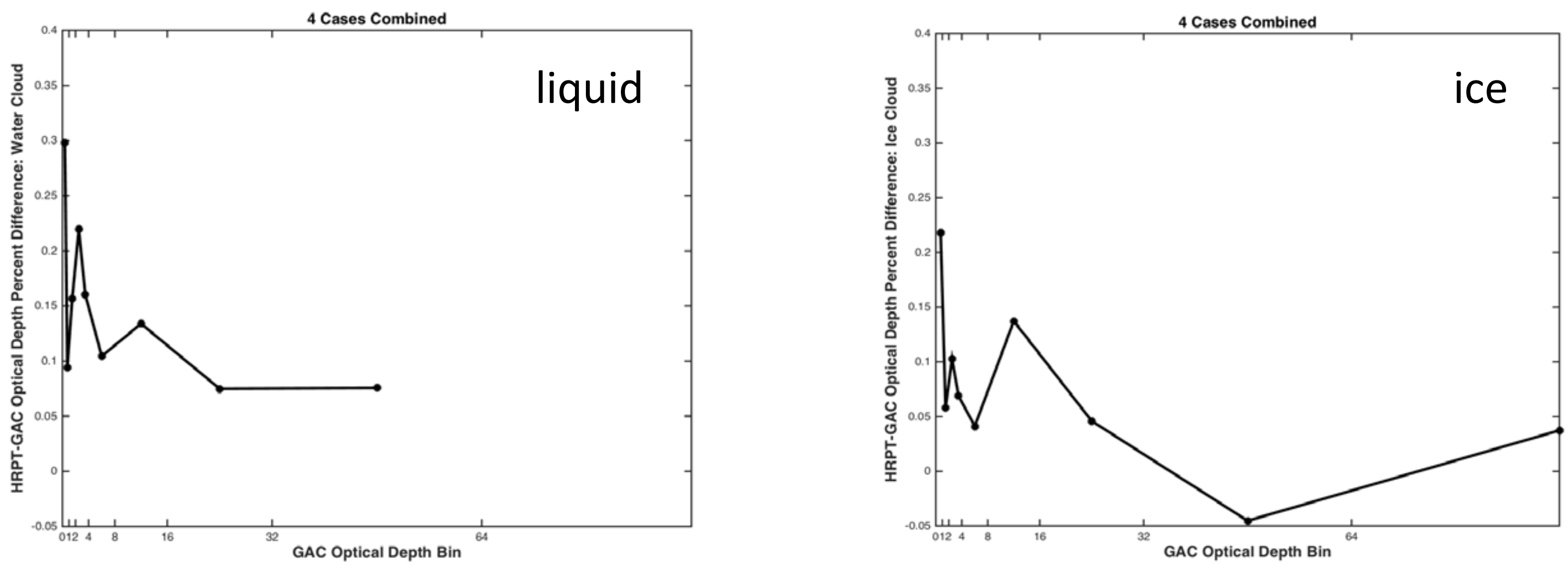
Phase	WATER			ICE		
Resolution	**1 km**	**2 km**	**4 km**	**1 km**	**2 km**	**4 km**
			CLOUD FRACTION			
Day	0.29	0.30	0.30	0.17	0.17	0.18
Night	0.17	0.17	0.17	0.32	0.32	0.32
Total	0.23	0.24	0.24	0.24	0.24	0.25
			CLOUD TOP PRESSURE (hPa)			
Day	693.2	699.4	707.2	400.4	404.4	410.4
Night	763.3	763.7	765.3	317.7	319.2	322.5
Total	720.4	723.8	729.0	345.9	348.8	353.8
			OPTICAL DEPTH			
Day	20.2	18.9	17.6	23.8	23.5	23.5
Night	11.6	11.3	10.8	5.8	5.7	5.6
Total	17.1	16.2	15.3	12.1	12.1	12.1

- slight increase (~0.01) in daytime cloud fraction expected
- 3.4 mb (~39 m) in increase (drop) liquid cloud pressure (alt)
- 2.9 mb (~62 m) in increase (drop) liquid cloud pressure (alt)
- 6% drop in optical depth expected in water clouds, no change in ice

Impact of GAC Averaging on Cloud Optical Depth Retrievals

- Dual gain satellites average 4 AVHRR 1-km pixel counts to obtain a 2-km GAC pixel
  - if pixels from both ranges averaged, then wrong average radiance computed
  - retrieved optical depth will be affected
  - no problem in homogeneous areas and very low sun
- Four 1-km HRPT tropical images were analyzed along with corresponding GAC image

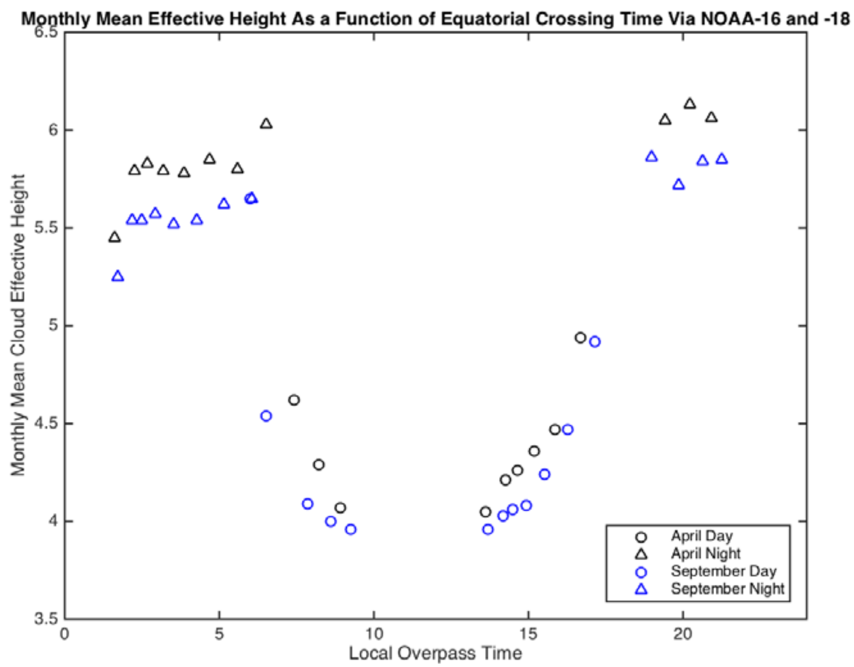
$[\ \tau(\text{HRPT}) - \tau(\text{GAC})\ ] / \tau(\text{GAC})$

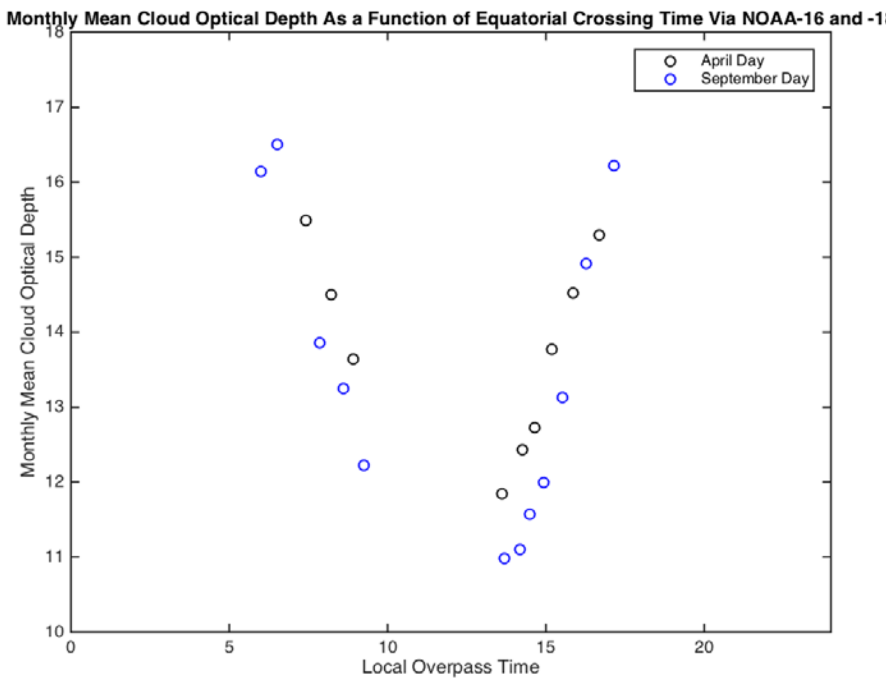


- cloud fraction change minimal
- cloud height change similar to MODIS study
- water cloud τ drops by 13%, ice cloud tau by 5%; total ~10%

Adjusting Means for Drifting Orbits

- To compare trends, must use same local time because of diurnal variability
- Normalize to Aqua MODIS 1330 ECT using normalization factors from N16 record
  - use monthly polynomial fits as function of ECT

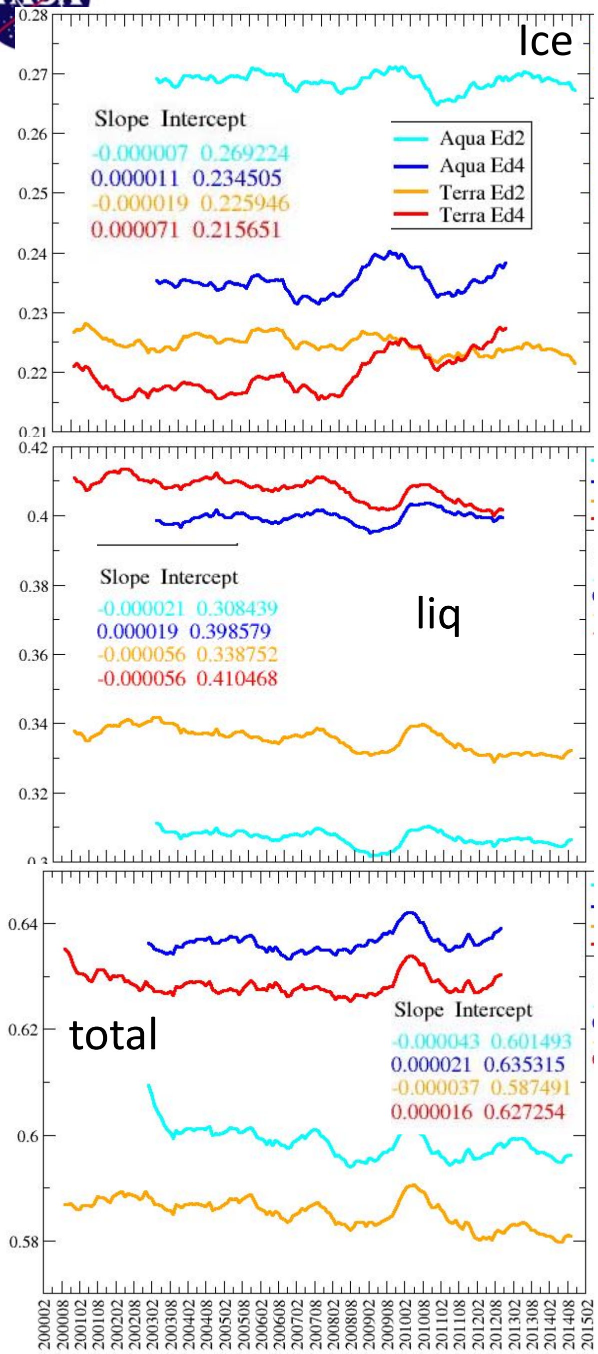




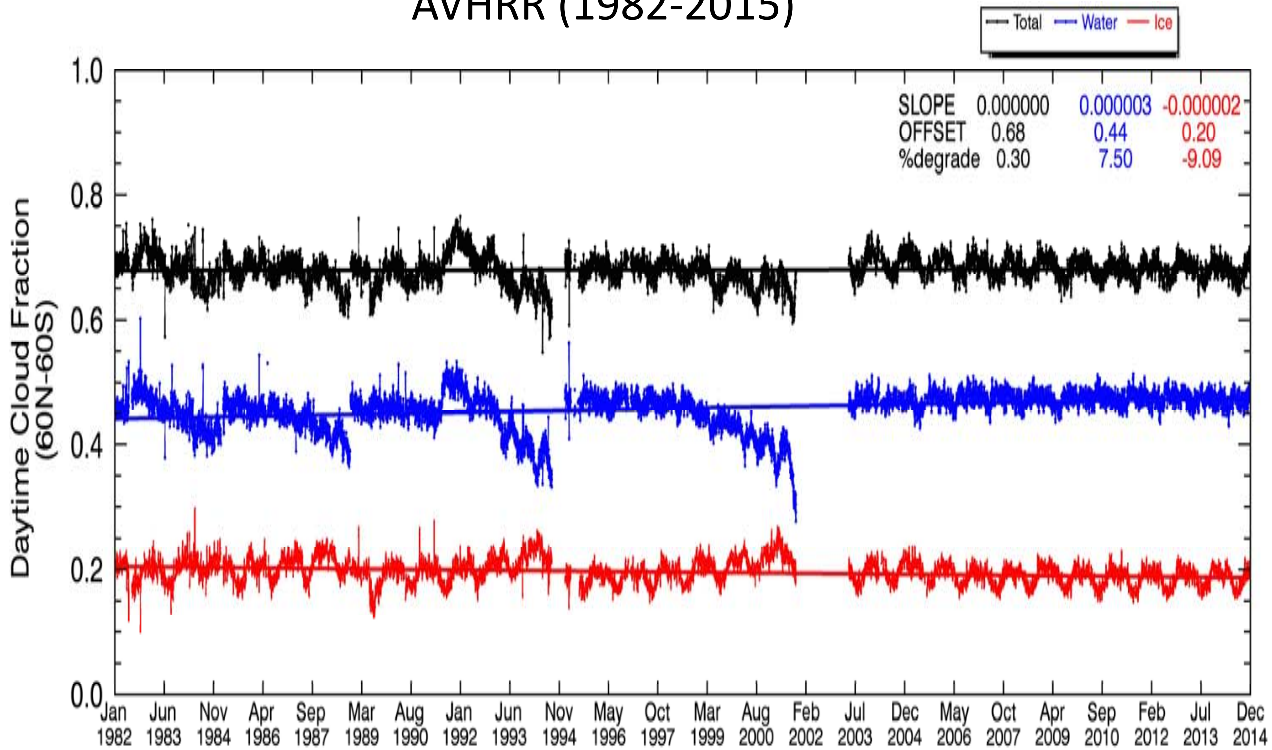
- Significant changes in cloud height and optical depth with local time
- All observations adjusted to 1330 ECT using ratios X(1330)/X(hour)

Mean Non-polar Daytime Cloud Fraction

MODIS (2000-2014)

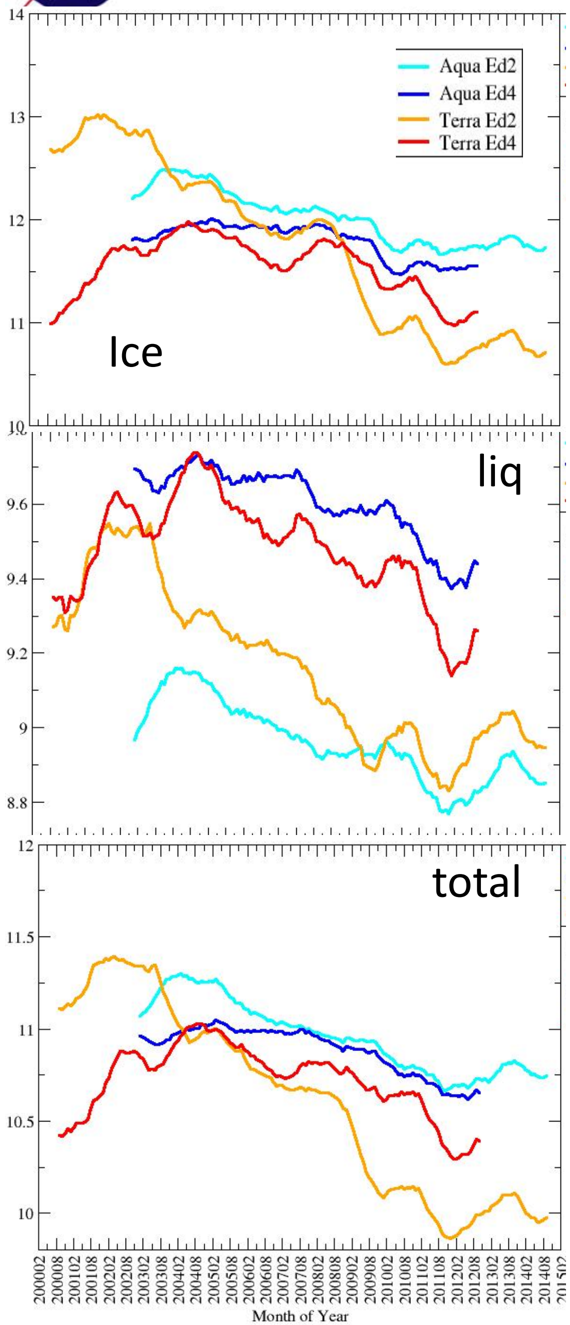


AVHRR (1982-2015)

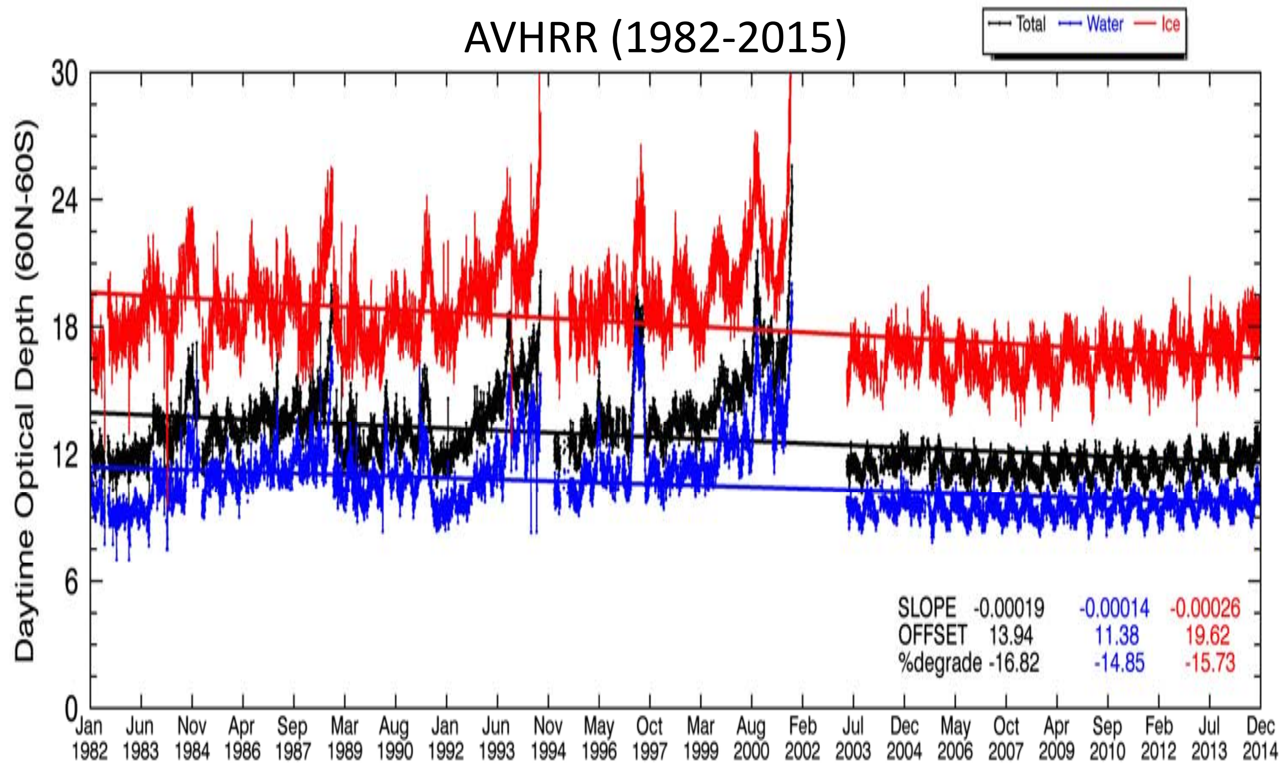


Mean Non-polar Daytime Cloud Optical Depth

MODIS (2000-2014)

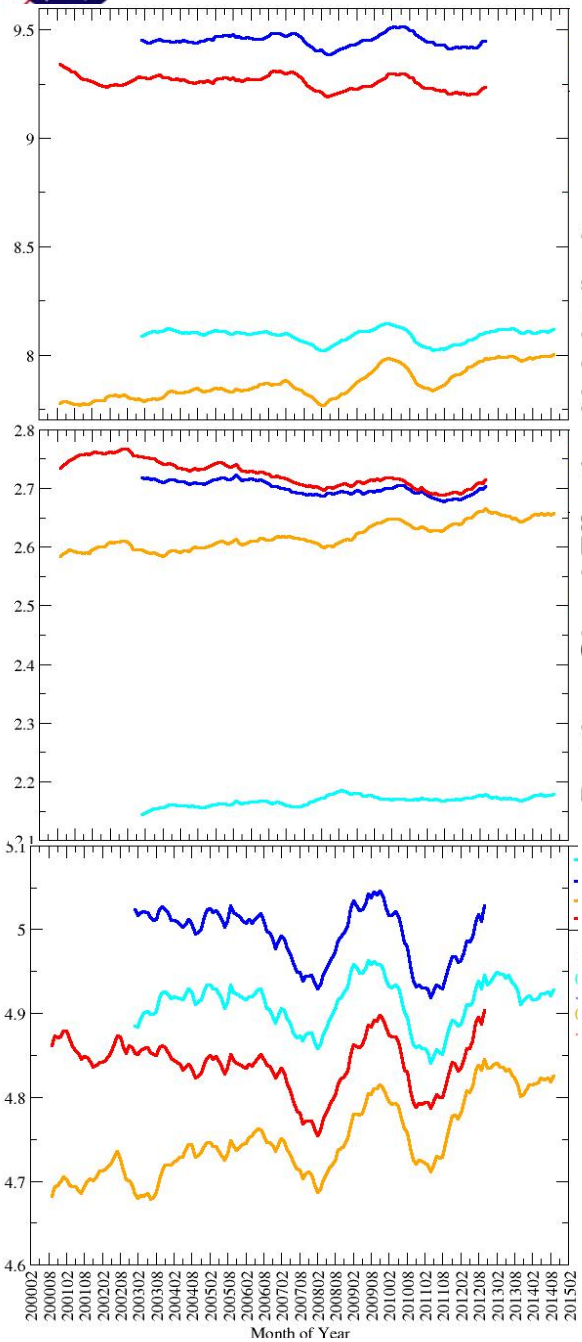


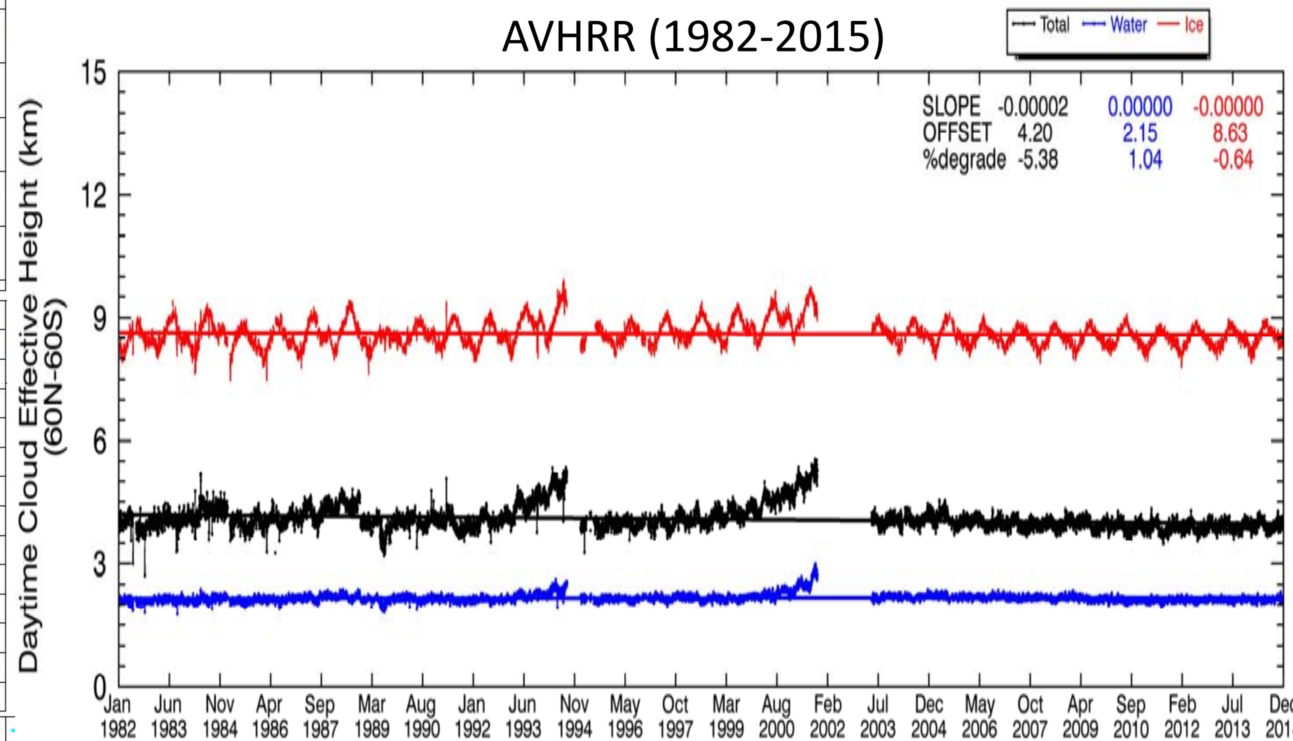
AVHRR (1982-2015)



Mean Non-polar Daytime Cloud Effective Height

MODIS (2000-2014)





- Trends total: Terra 27 m/dec, Aqua 65 m/dec, AVHRR 73 m/dec
  - MISR (1030 UTC): 44 ± 22 m/dec *(Davies et al. GRL, 2012)*
- AVHRR 1-km lower than Aqua on average
  - more small CU, no 13.3 or 1.38 µm
  - resolution effects

Conclusions

- Cloud property record derived from nearly identical algorithms from MODIS & AVHRR data (1982 – present, 1978-82 soon)
  - VIIRS to be added

- Results are mostly consistent, some differences due to
  - channel complements
  - spatial resolution
  - spectral bandwidths and noise (3.7 µm especially)
  - calibrations (e.g., Aqua MODIS VIS drifting, no AVHRR IR normalization)
  - sampling times
  - auxiliary data (NWP model analyses)

- small trend in cloud effective height during first decade of 2000
  - similar to that found using MISR data
  - consistent with SAGE trend in 80's and 90s

- Additional refinements needed to maximize compatibility

Future

- CERES Edition 5
  - use MODIS Collection 6 data, correct for Aqua drift after 2008
  - use new ice crystal and droplet models
  - adjust lapse rate constraints
  - apply optimal cloud-over-snow retrievals

- SatCORPS-A1b
  - Intercalibrate AVHRR IR channels for 35+ year time series
  - Improve low cloud height, relax constraints
  - Enhance overshooting top detection w/ improved IR & VIS pattern recognition
  - Test and possibly employ NASA MERRA-2 reanalysis
  - Enhance dynamic range of ice cloud optical depths at night using neural network
  - Add multilayer cloud and aerosol optical depth retrievals
  - Improve retrievals over snow/ice & cirrus retrievals during day
  - Examine GEOSat diurnal cycles to further enhance ECT corrections

- VIIRS Edition 2
  - use new ice crystal models
  - adjust lapse rate constraints
  - apply optimal cloud-over-snow retrievals